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Hubble and FUSE Studies of Ly α Absorbers at Low z

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Abstract. Ultraviolet spectrographs aboard the *Hubble Space Telescope* (HST) and the *Far Ultraviolet Spectroscopic Explorer* (FUSE) have proved their value as sensitive probes of the low-density intergalactic medium (IGM) at low redshifts ($z < 0.1$). Recent observations in Ly α , Ly β , and occasional higher Lyman lines show that warm photoionized gas in the low- z IGM may contain 20–25% of the baryons, with a $N_{\text{HI}}^{-1.8}$ distribution in column density. Measurements of resonance lines of Si III, C III, C IV, and O VI suggest that the metallicity of these absorbers ranges from 1–10% of solar abundance down to values below $0.003Z_{\odot}$. A comparison of Ly β /Ly α ratios (FUSE and HST) yields a distribution of Doppler parameters with $\langle b \rangle = 31.4 \pm 7.4 \text{ km s}^{-1}$ and median 28 km s^{-1} , comparable to values at $z = 2$ – 3 . The curve-of-growth (CoG) b -values are considerably less than widths derived from Ly α profile fitting, $\langle b_{\text{CoG}}/b_{\text{width}} \rangle = 0.52$, which suggests that low- z absorbers contain sizable non-thermal motions or velocity components arising from cosmological expansion and infall. A challenge for future UV spectroscopic missions (HST/COS and SUVO) is to obtain precision measurements of Ω_{IGM} and metallicities for the strong Ly α absorbers that dominate the IGM baryon content. This program will require accurate determinations of: (1) curves of growth using higher Lyman series lines; (2) the ionizing radiation field at 1–5 Ryd; and (3) characteristic sizes and shapes of the absorbers.

1. Introduction

For sheer sensitivity to interstellar or intergalactic H I, no technique compares with absorption lines of Ly α (1215.670 Å) and Ly β (1025.722 Å). Owing to its large dipole oscillator strength, Ly α is sensitive to gas with column density $N_{\text{HI}} \approx 10^{12.3} \text{ cm}^{-2}$, a million times lower than typically detected in 21-cm emission. It is little wonder that astronomers and cosmologists are drawn to Ly α studies as probes of the IGM, to investigate processes of galaxy formation, large-scale structure, IGM thermal history, and chemical evolution.

To understand these processes, which characterized the epoch when the first stars, galaxies, and heavy elements were formed, requires large ground-based telescopes and high-resolution spectrographs. At redshifts $z > 1.5$, sufficient to redshift H I Ly α into the visible, astronomers have thoroughly studied the “Ly α Forest” with the Keck/HIRES (Hu et al. 1995), VLT/UVES (Kim, Cristiani, & D’Odorico 2001), and other spectrographs. At lower redshifts, $z < 1.5$, one

must use ultraviolet telescopes to measure Ly α . To make the important connections between Ly α absorbers and signatures of galaxy formation and large-scale structure, it is best to probe the “local Ly α forest” at $z < 0.1$, where galaxy surveys and optical/21-cm imaging can detect galaxies well below the nominal L^* limit. It is this area of low- z IGM studies that has interested the Colorado group (Stocke et al. 1995; Shull et al. 1999a).

In its first several years, HST was used with the Faint Object Spectrograph (FOS) to carry out the QSO Absorption Line Key Project (Bahcall et al. 1991, 1993; Jannuzi et al. 1998; Weymann et al. 1998). Among its primary results was a characterization of the Ly α forest at $z < 1.5$ at low resolution (230 km s $^{-1}$) using strong Ly α lines (primarily with rest-frame equivalent width $W_\lambda > 240$ mÅ). In this review, I discuss our moderate-resolution (19 km s $^{-1}$) HST studies of the more numerous, weak Ly α lines ($W_\lambda \geq 10$ mÅ) using the Goddard High-Resolution Spectrograph (GHRS) and the Space Telescope Imaging Spectrograph (STIS). I also describe studies with the FUSE spectrograph, which has become a powerful probe of the IGM. With similar resolution (15–25 km s $^{-1}$) at wavelengths shortward of those accessible to HST and with LiF and SiC optics (Moos et al. 2000), FUSE provides access to the spectroscopically rich far-UV band (912–1187 Å) which contains Ly β , higher Lyman-series lines, and lines of key heavy elements, C III (977.03 Å) and O VI (1031.93, 1037.62 Å).

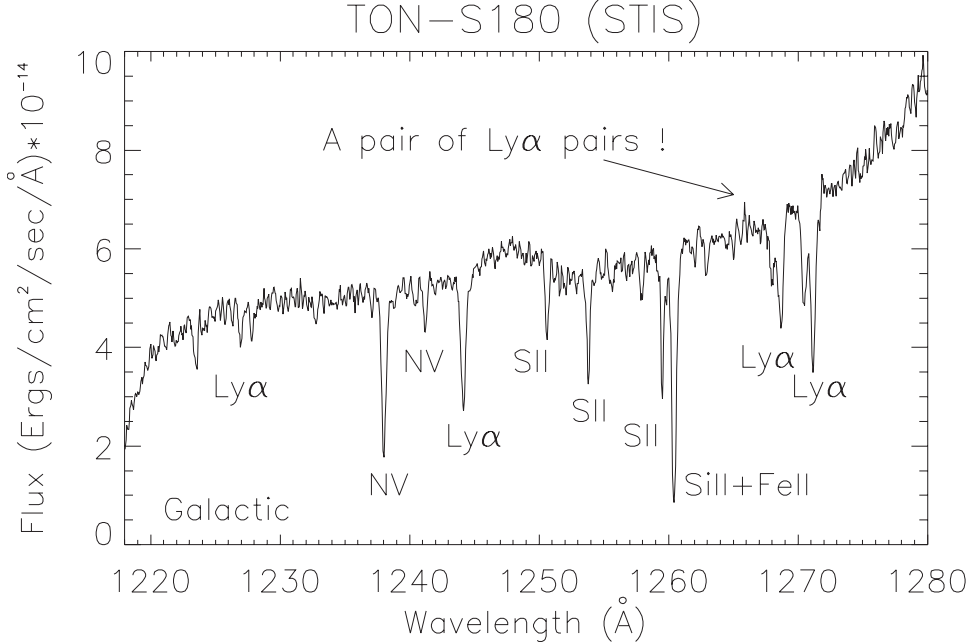


Figure 1. Typical STIS/G140M spectrum (Ton S180) from Penton et al. (2001b) showing a number of intergalactic Ly α absorbers, including a “pair of Ly α absorption pairs” between 1267–1272 Å. Galactic interstellar lines of N V, S II, and Si II/Fe II blend are also labeled.

Figure 1 shows a typical moderate-resolution spectrum taken by STIS. The Colorado survey results appear in a series of papers (Penton, Stocke, & Shull 2000; Penton, Shull, & Stocke 2000; Penton, Stocke, & Shull 2001a,b) that describe an analysis of 197 absorbers along sightlines to 31 AGN, over a total redshift pathlength $\Delta z = 1.15$. Preliminary FUSE results on the “Ly β forest” (Shull et al. 2000) have been followed by a number of papers on individual IGM sightlines, including PG 0953+415 (Savage et al. 2001), H1821+643 (Tripp et al. 2001), and 3C 273 (Sembach et al. 2001).

The enormous amount of data on high- z Ly α absorbers has constrained models for the growth of large-scale structure in the IGM. Similar comparisons can be made at low redshift, although the number of sightlines available for Ly α studies is far more limited. Among the desired H I statistics are the distribution in absorbers per unit redshift, dN/dz , and their distribution in column density N_{HI} . We also wish to understand the degree of clustering, the two-point correlation function in velocity, and any associations of absorbers with galaxies. However, the redshift pathlength currently available for moderate-resolution studies ($\Delta z \approx 1$) is much smaller than that surveyed at high- z . This disparity should change with the installation of the *Cosmic Origins Spectrograph* (COS) on HST in early 2004. Another QSO Absorption-Line Key Project with COS would be highly desirable.

2. Low-Redshift IGM Studies

2.1. Scientific Goals

It now appears likely that a substantial fraction of low- z baryons reside in the IGM, distributed in comparable amounts between hot shocked gas (Cen & Ostriker 1999; Davé et al. 2001) and warm photoionized Ly α absorbers (Shull et al. 1996, 1999a). At high redshifts, substantial progress has been made in linking these absorbers with the lowest density fluctuations of the baryon density; the statistics and physical properties of the absorbers are interpreted in terms of global models for the gravitational collapse of structure (Miralda-Escudé et al. 1996; Hernquist et al. 1996; Zhang et al. 1997). In a hierarchical dark matter-dominated cosmological framework, the evolution of the Ly α forest depends on the evolution of the dark matter and the thermal history of the IGM (Croft et al. 1999; Hui & Gnedin 1997; Schaye et al. 1999; Ricotti, Gnedin, & Shull 2000). Davé et al. (1999) show that the IGM overdensity–temperature relation (“effective equation of state”) may be extended to low redshift and measured by the quantities N_{HI} and b . We and others have pursued this idea theoretically and have used HST data to test it (Ricotti et al. 2000; Davé & Tripp 2001). However, until more observations are taken with the HST/STIS echelle (7 km s $^{-1}$ resolution), it will be difficult to define the true thermal line widths and perform reliable thermodynamic studies of the temperature evolution of the IGM.

With both FUSE and HST, our long-term goals are to characterize the amount and distribution of baryons in the low- z IGM and to define the extent of heavy-element transport in the IGM. Although many groups are continuing their studies of key individual sightlines, some of the most important long-term work involves large-scale surveys of Ly α , Ly β , and heavy elements. These surveys are

intended to “weigh the Ly α forest” (measure Ω_{IGM}) and determine the history of IGM metal production and transport away from their sources.

To perform these measurements accurately, one must detect both Ly α and Ly β , as well as the accessible UV resonance lines such as Si III λ 1206.50, Si IV λ 1393.76, 1402.77, C III λ 977.03, C IV λ 1548.20, 1550.77, and O VI λ 1031.93, 1037.62. Our work (Shull et al. 1999; Penton et al. 2000a,b) suggests that low- z Ly α absorbers are an important gaseous reservoir, with perhaps 25% of the baryons remaining in the IGM from the epoch of galaxy formation. However, because of the significant photoionization corrections required for this estimate, large uncertainties remain. Any accounting of the present-day distribution of baryons must include an accurate census of these clouds and the mass associated with them. As discussed in greater detail below (§3), precision measurements of the amount of warm (photoionized) IGM will take considerable effort. Not only must we characterize the absorber distribution in H I column density, but we must also apply a large ionization correction for the amount of unseen hydrogen in ionized form. This correction is straightforward, depending on the ratio, J_0/n_H , of ionizing background intensity to gas density. Although the gas density, n_H , is loosely related to the column density, N_{HI} , it is more accurately derived from the absorber geometry, including the characteristic scale length for variations in the gas distribution.

We would also like to use the H I line widths and Doppler parameters to understand the thermodynamical properties of the IGM. What is its temperature? When was energy deposited into the IGM from photoionization or bulk outflows? The Ly β /Ly α curves of growth yield reliable H I column densities of the saturated Ly α lines with $N_{\text{HI}} > 10^{13.5} \text{ cm}^{-2}$. Present estimates of the distribution in N_{HI} together with the expected photoionization correction ($\text{H}^+/\text{H}_{\text{tot}}$) suggest that the baryon content is dominated by the high end of the H I column-density distribution. In addition, observations of Ly β lines corresponding to the Ly α absorbers confirms the identification of any Ly α systems that may have been confused with metal lines intrinsic to the AGN.

2.2. Results of the HST Survey

Our HST data were taken toward AGN (quasars, Seyferts, BL Lacs) brighter than $B = 15.5$ mag, corresponding to UV spectral flux $F_\lambda \geq (1 - 2) \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$. Most of our targets were chosen to lie behind well-studied galaxy distributions, in order to probe the connection of the Ly α absorbers with large-scale distributions of galaxies and voids (see Figure 2 and the paper by Stocke in this volume). Our GHRS survey (Penton et al. 2000a,b) included 81 Ly α absorbers with line significance greater than 4σ , along 15 sightlines. With STIS, we have added 16 more AGN sightlines, bringing the survey total to 197 Ly α absorbers over a cumulative pathlength $\Delta z \approx 1.15$. Our survey yields a line frequency, $dN/dz \approx 200$ for $N_{\text{HI}} \geq 10^{13} \text{ cm}^{-2}$ at $z < 0.1$. The mean distance between such absorbers along the sightline is

$$\langle \ell_{\text{Ly}\alpha} \rangle = \frac{c/H_0}{dN/dz} \approx (20 \text{ Mpc}) h_{75}^{-1}, \quad (1)$$

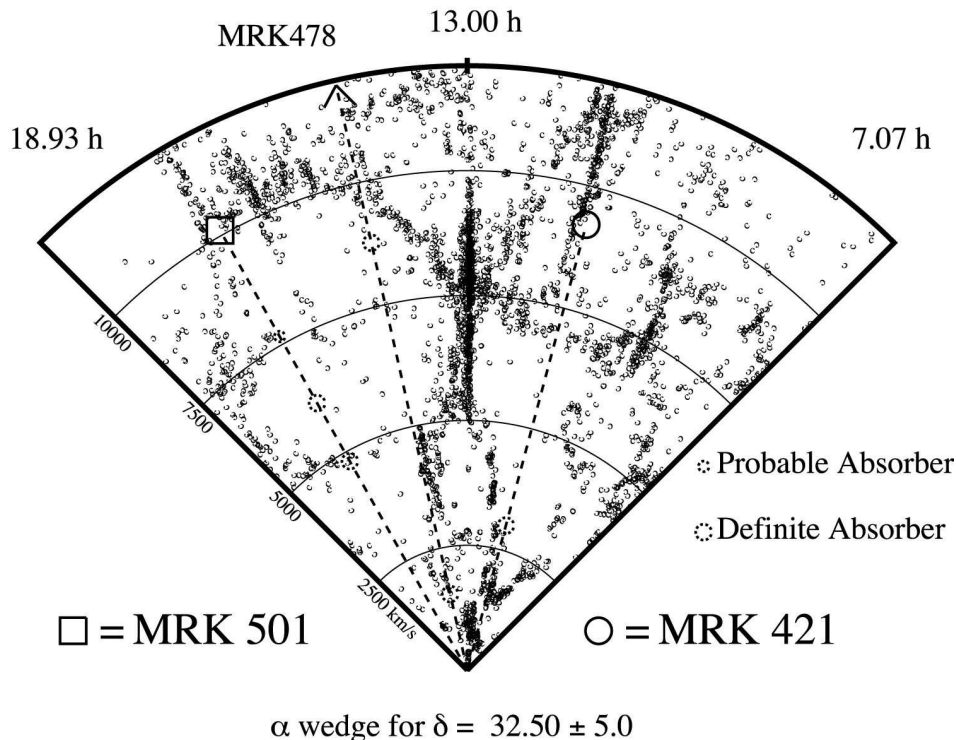


Figure 2. Locations of 3 sightlines used to study the low- z IGM toward Mrk 421, Mrk 501, and Mrk 478, in relation to large-scale filaments and voids in the distribution of bright galaxies (CfA survey). The positions of Ly α absorbers are shown as dotted circles, along sightlines to background sources.

for a Hubble constant $H_0 = (75 \text{ km s}^{-1} \text{ Mpc}^{-1})h_{75}$. This mean distance decreases by approximately a factor of 2, when we include the more numerous weak Ly α absorbers ($10 - 50 \text{ m}\text{\AA}$) with column densities $12.3 \leq N_{\text{HI}} < 13.0$.

In our GHRS/STIS survey of 197 Ly α absorbers (Penton et al. 2001b), the Ly α rest-frame equivalent widths range from $W_\lambda \approx 10 \text{ m}\text{\AA}$ to just above 1 \AA . For unsaturated Ly α lines, $N_{\text{HI}} = (9.2 \times 10^{12} \text{ cm}^{-2})(W_\lambda/50 \text{ m}\text{\AA})$. The H I column densities were derived using curves of growth (CoG) with Doppler parameters $b = 25 \pm 5 \text{ km s}^{-1}$. The W_λ distribution exhibits a significant break at $W_\lambda < 133 \text{ m}\text{\AA}$, with an increasing number of weak absorbers ($10 - 100 \text{ m}\text{\AA}$). These weak Ly α absorbers provide the most numerous and extensive probes of low-density regions of the IGM. We characterize the distribution in H I column densities (Figure 3) as a power law,

$$dN/dN_{\text{HI}} \propto N_{\text{HI}}^{-\beta}. \quad (2)$$

At the low-column end, the slope is somewhat steeper, $\beta = 1.82 \pm 0.10$ ($12.3 < \log N_{\text{HI}} < 14.0$), while $\beta = 1.42 \pm 0.16$ for the saturated Ly α absorbers ($14.2 < \log N_{\text{HI}} < 15.6$). These values are similar to those found in the high-redshift Ly α forest (Kim et al. 1997, 2001). Figure 4 shows the evolution of strong and weak Ly α absorbers with redshift, over the interval $0 < z < 3.7$.

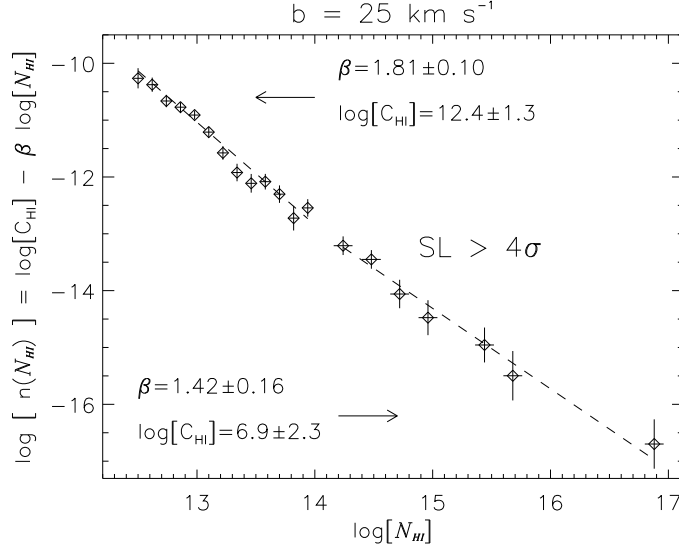


Figure 3. The distribution of H I column densities in the combined GHRS/STIS survey (Penton et al. 2001b) for 197 Ly α absorbers at significance level 4σ or greater. The weak absorbers fit a power law $N_{\text{HI}}^{-1.81 \pm 0.10}$ while absorbers above 10^{14} cm^{-2} follow a distribution $N_{\text{HI}}^{-1.42 \pm 0.16}$.

2.3. FUSE Studies of the Ly β Forest

One of the Early Release Observations of the FUSE program was a moderate-resolution ($20\text{--}25 \text{ km s}^{-1}$) study of the low-redshift IGM (Shull et al. 2000). Our team carried out studies of 7 extragalactic sightlines and 12 Ly β absorbers that correspond to Ly α lines detected by HST/GHRS and STIS. In general, we detect Ly β absorption for all Ly α systems with $W_\lambda > 200 \text{ m}\text{\AA}$. This is not surprising, since for unsaturated lines, the equivalent widths are: $W_\lambda(\text{Ly}\alpha) = (54.5 \text{ m}\text{\AA})(N_{\text{HI}}/10^{13} \text{ cm}^{-2})$ and $W_\lambda(\text{Ly}\beta) = (7.37 \text{ m}\text{\AA})(N_{\text{HI}}/10^{13} \text{ cm}^{-2})$. Even considering line saturation, the Ly β line should have equivalent width $W_\lambda(\text{Ly}\beta) \geq W_\lambda(\text{Ly}\alpha)/7.4$. Using FUSE data, with $30\text{--}40 \text{ m}\text{\AA}$ (4σ) Ly β detection limits, we employed the equivalent width ratio of Ly β /Ly α and occasional higher Lyman lines to determine the Doppler parameters, b_{CoG} , and column densities, N_{HI} , for moderately saturated lines. The Ly β /Ly α technique is demonstrated in Figure 5, which shows the CoG concordance for the strong 1586 km s^{-1} Ly α absorber toward 3C 273. In this case (Sembach et al. 2001), we detect the first 8 Lyman lines (Ly α through Ly θ). Surprisingly, the CoG-inferred column density and b -value differ considerably from those derived from Ly α profile fitting.

From a CoG analysis, the Ly β /Ly α ratios in our FUSE survey (Shull et al. 2000) yield a preliminary distribution function of Doppler parameters, with mean $\langle b \rangle = 31.4 \pm 7.4 \text{ km s}^{-1}$ and median $b = 28 \text{ km s}^{-1}$, comparable to values at redshifts $z = 2\text{--}3$. If thermal, these b -values correspond to $T_{\text{HI}} = (m_H b^2 / 2k) \approx 50,000 \text{ K}$, too hot for purely photoionized clouds (Donahue & Shull 1991). However, we find some evidence that the line widths are not entirely thermal. The CoG-inferred Doppler parameters are considerably less than the

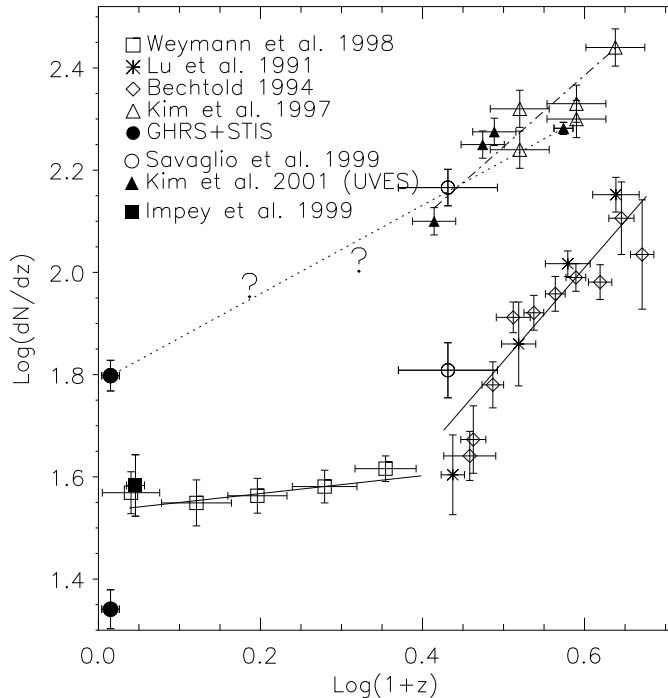


Figure 4. Distribution of the line frequency, dN/dz , of strong and weak Ly α absorbers with redshift. Results from our GHRs/STIS survey are shown as solid filled circles at $z \approx 0$ (Penton et al. 2001b). Top curve shows weak absorbers ($13.1 \leq \log N_{\text{HI}} \leq 14.0$) from Keck/HIRES and VLT/UVES (Kim et al. 1997, 2001) at $z > 1.6$, extrapolated down to the $z \approx 0$ point (GHRs/STIS). Bottom curve shows the evolution of strong absorbers ($W_{\lambda} \geq 240 \text{ m\AA}$ or $\log N_{\text{HI}} \geq 14$) from ground-based surveys (Bechtold et al. 1994; Savaglio et al. 1999), extrapolated below $z < 1.5$ with the HST Key Project (Weymann et al. 1998), a low-resolution HST/GHRs/G140L study (Impey, Petry, & Flint 1999), and down to $z \approx 0$ with our moderate-resolution GHRs/STIS survey.

widths derived from Ly α profile fitting, $\langle b_{\text{CoG}}/b_{\text{width}} \rangle = 0.52$. The combined HST/FUSE data suggest that the low- z Ly α absorbers contain significant non-thermal motions or velocity components in the line profile, perhaps arising from cosmological expansion and infall.

Because the CoG generally produces lower b -values, the derived H I column densities increase. The typical increase over that derived from Ly α profile fitting is $\Delta[\log N_{\text{HI}}] = 0.3$, but it can increase by more than a factor of 10. In an extreme case (Figure 5) the 1586 km s^{-1} absorber toward 3C 273 increased in column density by a factor of over 40, to $\log N_{\text{HI}} = 15.85^{+0.10}_{-0.08}$ (Sembach et al. 2001) compared to the value, $\log N_{\text{HI}} = 14.22 \pm 0.07$, determined from Ly α profile fitting (Weymann et al. 1995). This large change in N_{HI} arose because the curve of growth gave a Doppler parameter $b_{\text{CoG}} = 16 \text{ km s}^{-1}$, while Ly α profile fitting gave $b_{\text{width}} = 34.2 \pm 3.3 \text{ km s}^{-1}$.

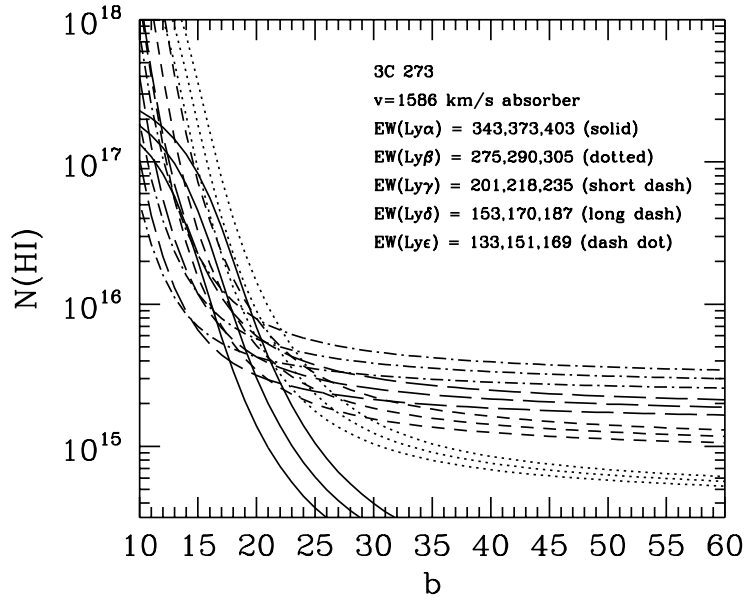


Figure 5. Curve of growth concordance plot (Giroux & Shull, unpublished) in b (km s^{-1}) and N_{HI} (cm^{-2}) for the $\text{Ly}\alpha$, $\text{Ly}\beta$, and higher Lyman lines in the strong absorber at $cz = 1586 \text{ km s}^{-1}$ toward 3C 273. Three curves for each Lyman line show single-component, Doppler-broadened CoG fits to equivalent widths (labeled in $\text{m}\text{\AA}$ with $\pm 1\sigma$ errors.) The best fit for $\text{Ly}\beta$ and higher lines yields $\log N_{\text{HI}} = 15.85^{+0.10}_{-0.08}$ and $b = 16.1 \pm 1.1 \text{ km s}^{-1}$ (Sembach et al. 2001), considerably different from the values, $\log N_{\text{HI}} = 14.22 \pm 0.07$ and $b = 34.2 \pm 3.3 \text{ km s}^{-1}$, from $\text{Ly}\alpha$ profile fitting (Weymann et al. 1995).

2.4. Metallicities

Determining the intergalactic heavy-element abundance (metallicity) of ionization state (i) of element (Z) depends in the first instance on measuring accurate column densities, N_{HI} and $N_{Z,i}$. As discussed above, N_{HI} can be particularly sensitive to CoG effects arising from line saturation; the combination of $\text{Ly}\alpha$ and higher Lyman lines is often needed to fix the b -value. One must then apply an ionization correction, to convert the ratio $N_{Z,i}/N_{\text{HI}}$ to a total abundance N_Z/N_H . If the absorbing gas is photoionized, this ionization correction is straightforward (Donahue & Shull 1991; Shull et al. 1998) if one knows the intensity and spectrum of the metagalactic background radiation and the physical density, n_H , of the absorber. In practice, one computes the ionization correction as a function of the dimensionless “photoionization parameter”, $U = n_\gamma/n_H$, where n_γ is the number density (cm^{-3}) of Lyman-continuum photons and n_H is the number density of hydrogen nuclei. The situation becomes more complicated if the absorber’s physical conditions include collisional ionization in hotter gas, such as the O VI absorbers seen by Tripp, Savage, & Jenkins (2000).

Metallicity limits in several low- z $\text{Ly}\alpha$ clouds have been set for the strong $17,000 \text{ km s}^{-1}$ absorbers toward PKS 2155-304 (Shull et al. 1998). The absence of detectable Si III $\lambda 1206.5$ or C IV $\lambda 1548.2$ sets limits of less than 0.003 solar. Other promising systems $\text{Ly}\alpha$ systems have been found, including two strong

Ly α absorbers toward PG 1211+143 (see Figure 6). With rest-frame equivalent widths of 1.14 Å and 0.89 Å, these absorbers are among the strongest detected in our GHRs/STIS sample, and they appear to show heavy elements at the level of several percent solar metallicity. Additional studies of Ly α absorbers with $W_\lambda > 200$ mÅ are currently underway with both FUSE and HST.

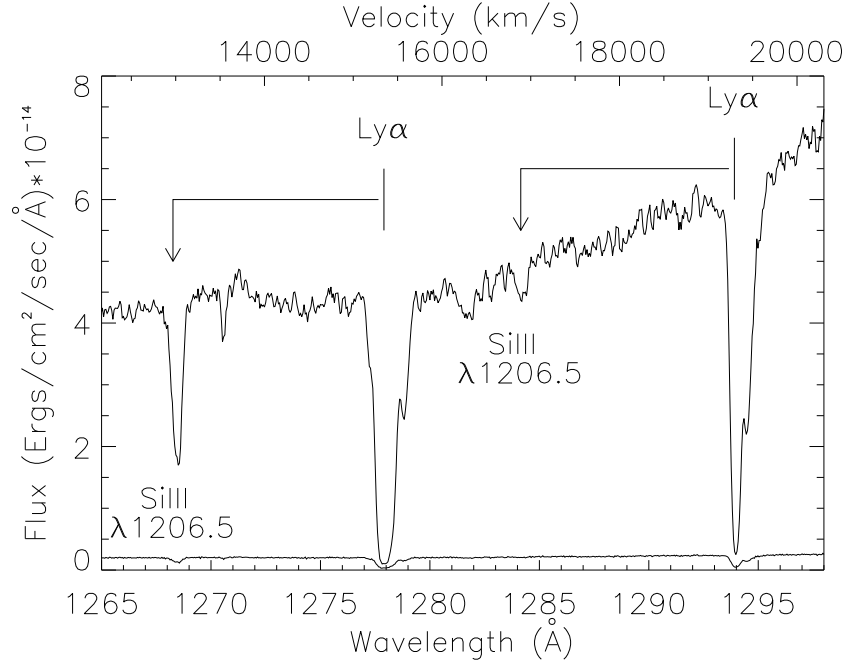


Figure 6. Section of our STIS/G140M observations of PG 1211+143, showing two strong Ly α absorbers at $cz = 15,300$ and $19,400$ km s $^{-1}$, with rest equivalent widths of 1145 ± 115 mÅ and 893 ± 90 mÅ, respectively. Each of these absorbers appears to have multiple velocity components. The two arrows show the expected locations of the Si III $\lambda 1206.50$ line, although the feature at 1268.3 Å is actually another Ly α absorber (confirmed by Ly β).

3. Toward Precision Measurements of the IGM Baryon Content

The primary ingredients for making accurate measurements of the contribution of low- z Ly α absorbers to Ω_b are:

- Accurate H I column densities, derived from a CoG analysis of Ly α , Ly β , and occasional higher Lyman lines.
- Knowledge of the ionizing radiation field, needed to derive the photoionization corrections for total abundances.
- An estimate of the physical density, n_H , from independent determinations of H I absorber sizes, shapes, and gas distribution.

Toward these ends, we are attempting to accumulate a sufficiently large database of Ly α and Ly β absorbers with HST and FUSE to characterize the distribution in N_{HI} . However well one can determine the N_{HI} distribution, one still must deal with absorber geometric issues that produce systematic uncertainties in the ionization corrections.

One of the best ways to make progress is to find a “constellation of AGN” whose UV spectra can be cross-correlated for common Ly α absorption lines to infer their characteristic sizes. At the current flux limits of the 2.4m HST, this is a difficult experiment, but there is hope with the planned (Jan. 2004) installation of the *Cosmic Origins Spectrograph* (COS) on HST. With 10–20 times greater throughput than STIS, COS will be able to obtain moderate resolution (15–20 km s $^{-1}$) spectra toward AGN as faint as 18 mag. As shown in Table 1, this greatly increases the chances of finding multiple bright QSOs separated by $\sim 30'$. With a sufficient number of AGN background sources behind low- z Ly α absorbers, one can make rudimentary “tomographic maps” of the cosmic web of warm (photoionized) baryons left over from the epoch of large-scale structure formation.

Mapping the evolution of these gaseous structures down to low z is a prime scientific goal of COS. The full experiment must await the powerful 6–8m successor to HST, a mission concept known as the *Space Ultraviolet-Visible Observatory* (SUVO). The scientific and technological rationale for SUVO is contained in the “White Paper” from the UV-Optical Working Group (Shull et al. 1999c) available on the Web at <http://origins.colorado.edu/uvconf/UVOWG.html>.

Table 1
QSO Counts and Mean Angular Distance^a Between QSOs

m_B (magn)	N_{QSO} (sqdeg $^{-1}$)	θ_{QSO} (arcmin)
16	0.01	300'
17	0.13	83'
18	1.1	29'
19	5.3	13'
20	17	7.3'
21	41	4.7'

^a Mean angular distance $\theta_{\text{QSO}} = (1/2)N_{\text{QSO}}^{-1/2} = (30')N_{\text{QSO}}^{-1/2}$ between Poisson-distributed QSOs of frequency N_{QSO} per square degree (see Shull et al. 1999c).

To thoroughly map the cosmic web, we need to observe QSOs at magnitudes down to $m_B \approx 20 - 21$, where the mean angular distance between QSOs on the sky is $\leq 10'$, allowing for lower UV continuum fluxes owing to potential extinction. After accounting for ultraviolet absorption from Lyman-limit systems, Picard & Jakobsen (1993) found a steep rate of increase, $d(\log N)/d(\log F_\lambda) = 2.7 \pm 0.1$ for quasars in the flux range 10^{-14} down to 10^{-16} ergs cm $^{-2}$ s $^{-1}$ Å $^{-1}$ (approximately $m_B = 15$ down to $m_B = 20$). The current limit of HST/STIS for moderate-resolution spectroscopy is $m_B \approx 15.5$, while

HST/COS will take this limit to $m_B \approx 18$. Another order-of-magnitude improvement is required to capitalize on the large increase in QSO populations at magnitudes $m_B = 18 - 20$.

In the next several years, the GALEX mission is expected to identify large numbers of QSOs in the magnitude range $18 < m_B < 20$. The Sloan survey will provide redshifts for many of these targets. The task of mapping the IGM structures from $z = 2$ down to $z = 0$ will be a highlight of the SUVO program, if its spectrographs are designed with sufficient throughput to undertake a major survey of sightlines at high spatial frequency. The goal is to make an IGM baryonic survey on sub-degree angular scales, comparable to that of the MAP explorer and to the structure seen in galaxy surveys. In doing so, we will connect the high-redshift seeds of galaxies and clusters with the distributions of galaxies and IGM in the modern epoch, at redshifts $z < 1$.

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